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Herd-level economic losses associated with Johne's disease on US dairy operations

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Abstract

Johne's disease ('paratuberculosis') is a chronic, infectious, wasting disease that affects dairy cattle. Estimation of its impact on herd productivity and corresponding economic loss on US dairy operations was part of the USDA National Animal Health Monitoring System's (NAHMS) 1996 national dairy study. Johne's-positive herds experience an economic loss of almost US$ 100 per cow when compared to Johne's-negative herds due to reduced milk production and increased cow-replacement costs. For Johne's-positive herds that reported at least 10% of their cull cows as having clinical signs consistent with Johne's disease, economic losses were over US$ 200 per cow. These high-prevalence herds experienced reduced milk production of over 700 kg per cow, culled more cows but had lower cull-cow revenues, and had greater cow mortality than Johne's-negative herds. Averaged across all herds, Johne's disease costs the US dairy industry, in reduced productivity, US$ 22 to US$ 27 per cow or US$ 200 to US$ 250 million annually. Published by Elsevier Science B.V.

Keywords: *Mycobacterium paratuberculosis*; Johne's disease; Economics; Cattle-microbiological diseases; NAHMS

1. Introduction

Johne's disease (paratuberculosis) is a chronic infectious disease of domestic and exotic ruminants, including dairy and beef cattle, sheep, goats, cervids, and camelids. The disease is caused by *Mycobacterium paratuberculosis* and occurs worldwide. *M.*

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paratuberculosis is a slow-growing bacterium that causes thickening of the intestinal wall of cattle; the thickening reduces absorptive capability. Johne's disease in cattle and other species is characterized by chronic, granulomatous degenerative enteritis that causes intermittent but persistent diarrhoea, progressive weight loss, and eventual death. The disease is untreatable and slowly progressive (Stehman, 1990).

On dairy farms, economic losses occur through premature culling, reduced milk production, and body-weight losses in slaughter cattle. In a recent summary of production studies by Nordlund et al. (1996), Johne's-infected cows produced from 2 to 19% less milk then their herdmates. These losses associated with Johne's disease led the dairy industry to request that economic analysis of Johne's disease be an objective for US Department of Agriculture (USDA) National Animal Health Monitoring Systems' (NAHMS) 1996 national dairy survey known as Dairy '96.

2. Methodology

2.1. Dairy survey

In January 1996, the first phase of Dairy '96 began with an interview of a stratified random sample of 2542 dairy producers in 20 selected states (Fig. 1.). This survey represented 83% of US dairy cows and questionnaires were administered by USDA's National Agricultural Statistics Service enumerators to collect herd health and management information. Participating producers with at least 30 milk cows were asked to continue in the second phase of the study. During the second phase, USDA or state veterinary medical officers or animal-health technicians administered another questionnaire and collected blood samples from a sample of 25 to 40 milk cows per participating herd, selected to represent the distribution of cows in the herd. This second questionnaire assessed producer familiarity with and recognition of Johne's disease and use of management practices associated with the disease. A total of 1219 dairy producers completed the second questionnaire with 1004 agreeing to serum testing for *M. paratuberculosis* (USDA:APHIS, 1997).

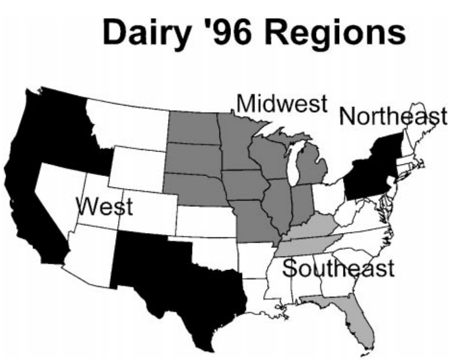

Fig. 1. Participating states in the US Department of Agriculture's National Animal Health.

The purpose of serum testing was to estimate herd prevalence for Johne's disease. The serum samples collected were sent to USDA's National Veterinary Services Laboratories for *M. paratuberculosis* antibody testing using a commercially available enzyme-linked immunosorbant assay (ELISA, IDEXX Laboratories, Westbrook, ME). The IDEXX ELISA test has a reported test sensitivity of 45 to 50% and test specificity of 99.0 to 99.7% (Collins and Sockett, 1993 and Sweeney et al., 1995). Because the test has low sensitivity, 25 to 40 cows per herd (depending on herd size) were tested to ensure (at the 90% confidence level) finding at least one positive cow if the within-herd prevalence was at least 10%. Evaluating many cows per herd using a test with imperfect specificity, however, results in some truly negative herds with one or more false positive cows. Thus, Johne's-negative herds could be misclassified as Johne's-positive.

One way to reduce the number of false-positive herds is to increase the number of test-positive cows to two before classifying the herd as being positive with Johne's disease. The trade-off is decreased herd sensitivity – that some truly positive herds that had only one test-positive cow would now be classified as Johne's-disease negative. To help classify herds with one test-positive cow, we incorporated historical information provided by producers about clinical signs of Johne's disease in cows culled during the previous 12 months. Among herds with one test-positive cow if $\geq$5% of cull cows within the past year showed clinical signs consistent with Johne's disease, then the herd was classified as being Johne's-disease positive; otherwise, herds with one test-positive cow were classified as Johne's-disease negative. All herds with $\geq$2 test-positive cows were classified as Johne's-positive herds regardless of the percentage of cull cows with clinical signs. (For more detail on classification of herds for Johne's disease see USDA:APHIS, 1997).

2.2. Economic model

To estimate the economic loss of Johne's disease on US dairy operations, we used a multivariable regression model. We chose a multivariable regression model in order to explain as much of the variance as was practically possible in order to minimize potential confounding affects.

2.2.1. Dependent variable: adjusted value of production

The model measured economic loss associated with Johne's disease on a per-milk-cow (1 January 1996 inventory) basis. Economic loss from Johne's disease included losses such as reduced milk production and salvage value for clinically affected cattle at cull-cow markets. Also included was value of calves born alive because herds with Johne's disease would be expected to market a higher proportion of pregnant cows than herds without the disease. On the cost side, expected higher culling and mortality risks and the resulting increase in number of cow replacements would increase costs. Data on other costs such as feed, labor, or veterinary expenses were not collected. Thus, we could not measure a change in net farm income – so the term 'adjusted value of production' was used to include both revenue and some cost changes.

$$\text{Annual adjusted value of production} = \text{annual value of milk production} + \text{annual value of calves at birth} - \text{annual net replacement cost}$$

where

$$\text{annual net replacement cost} = \text{annual value of milking cows sold (cows sold to other producers)} + \text{annual value of cull cows (cows sold for slaughter)} - \text{annual value of replacement cows.}$$

Milk-production value: annual value of milk production was reported annual rolling herd average per cow multiplied by a milk price of US$ 286.60 per metric tonne (US$ 13/cwt) – the average milk prices during the study (January 1995 to July 1996) (USDA:NASS, 1997).

Calf value: annual value of calves at birth on a per cow basis equals total number of calves born alive divided by 1 January 1996 cow inventory multiplied by US$ 50 per head calf price. (Average of US$ 75 for day-old heifer calves and US$ 25 for day-old bull calves, based on prices reported in *The Western Dairyman*, June 1996) We assumed that Johne's disease did not affect preweaned calves or heifers (and thus, their rearing was considered as a separate enterprise and was excluded from this analysis).

Value of milking cows sold: annual value of cows sold for dairy purposes to other producers on a per cow basis equals total number of such cows divided by 1 January 1996 cow inventory multiplied by a cow price of US$ 1100 per head (based on average prices received for replacement cows, January 1995 to July 1996 (USDA:NASS, 1997)).

Cull cow value: value of culled cows on a per cow basis has two components: culls in normal body condition and culls in poor body condition. Producers were asked how many cull cows in the previous 90 days were in normal body condition and in poor body condition (low 'cutter' or 'canner' grade; these are marketing grades in the US) and the per-head price received for each category. Cull cows in normal or poor body condition were estimated by multiplying total cull cows by the proportion of cull cows in each category from the 90-day period. Total value was then determined by multiplying the number of cull cows in each category by the price received per head for each category. The value of cull cows on a per-milk-cow basis was estimated by dividing total cull-cow value by the 1 January 1996 cow inventory.

Some producers did not report any cows culled during the previous 90 days. Most (89 of 101) of the producers who had no culls during the previous 90 days milked less than 100 cows. We did not want to exclude them from the analysis due to missing data, so we assumed that their proportion of poor conditioned cull cows was the same as other producers in the same herd size group and region of the country. For these producers and an additional 55 producers with cull cows but no reported cull-cow prices, median prices from each size-region combination were substituted for the missing-price data. Nationally, producers reported median price for normal-conditioned culls of US$ 400 per head and US$ 250 per head for poor-condition culls.

Replacement cost: the cost of a replacement cow was assumed to be US$ 1100 per cow (USDA:NASS, 1997) and when multiplied by the number of replacement cows gives total-herd replacement cost. Total-herd replacement cost divided by 1 January 1996 inventory gives replacement cost on a per-cow basis. Data were collected on number of bred heifers, milking cows, and dry cows that were brought onto the operation during 1995. The number of raised heifers added to the milking string was not collected. Therefore, we assumed that the number of raised heifers that entered the milking string in 1995 equaled the number of first-calf heifers on 1 January 1996 minus bred heifers that were brought onto the dairy operation during 1995. Cow replacement then equaled the number of farm-raised heifers plus the number of bred heifers, milking cows, and dry cows that were brought onto the operation during 1995.

To determine the impact of individual components (individual herd-productivity measures) on annual adjusted value of production the components were substituted as the dependent variable in the regression model and estimates were then determined for each component.

2.2.2. *Johne's explanatory variables*

Two models were developed based on herd classification of Johne's disease. For Model I, herds were classified as being either Johne's-disease negative or Johne's-disease positive based on the definition discussed earlier. Model I was developed for three reasons. First, we recognized that other diseases and conditions such as salmonellosis, winter dysentery, and intestinal parasitism, can cause similar clinical signs as Johne's disease. Comparing Johne's-disease positive herds to Johne's-disease negative that had these other disease conditions would underestimate the impact of Johne's when compared to healthy herds.

Second, we wanted to investigate how within-herd Johne's-disease prevalence affected results. Unfortunately, our Johne's-disease testing protocol did not allow the estimation of within-herd prevalence. Instead, we used percent cull cows with clinical signs consistent with Johne's disease as a proxy measure of the severity of Johne's disease within the herds. Herds which had <10% cull cows showing Johne's disease clinical signs in the previous 12 months were placed into the low-prevalence Johne's-positive group, while those with $\geq$10% cull cows with clinical signs were placed into the high-prevalence Johne's-positive group.

Finally, instead of lumping all the Johne's-disease-negative herds that also had cull cows with clinical signs consistent with Johne's disease, we also divided them at the '10% showing signs' cull-cow level Such a division allowed us to compare Johne's disease to other agents that cause similar clinical signs. Thus, Model II had the following herd classifications:

1. Johne's-disease negative, no reported cull cows with clinical signs;
2. Johne's-disease negative, >0% but <10% cull cows with reported clinical signs;
3. Johne's-disease negative, $\geq$10% cull cows with reported clinical signs;
4. Johne's-disease positive, cull cows with reported clinical signs <10%;
5. Johne's-disease positive, $\geq$10% cull cows with reported clinical signs.

Johne's-negative herds with no reported cull cows with clinical signs consistent with Johne's disease in the previous 12 months were used as the reference variable in the regression analyses.

2.2.3. Other explanatory variables

Both models were offered the same (non-Johne's disease) explanatory variables because of their expected relationship to milk production per cow. The other explanatory variables were:

- Herd size. Initial analysis determined that a non-linear relationship existed between herd size and milk production. This non-linear relationship was modeled as continuous variable by taking the natural log of the 1 January inventory number of milk cows.
- Region. Data were collected from four milk-producing regions in the US: midwest, west, southeast, and northwest (Fig. 1).
- Use of Dairy Herd Improvement Association (DHIA) records DHIA use (yes/no) served as a proxy measure of management capability.
- Intensive pasture grazing (yes/no), was defined as use of pastures for $\geq$90% of summer forage requirements.
- Percent bovine somatotropin (bST) use. Initial analysis demonstrated a non-linear relationship between milk production and percent bST use. This non-linear relationship was modeled as a continuous variable by transforming percent bST use into square root of percent bST use. The square-root transformation was used in part because of the large number of herds that did not use any bST.
- Bulk-tank somatic-cell count. Three levels were used: <200 000 cells/ml, 200 000–399 999 cells/ml, $\geq$400 000 cells/ml. The <200 000 cells/ml level served as the reference category.
- Percent Holstein breed among milk cow inventory, a continuous variable.
- Length of time dairy cows were dry (not in milk): <70 days or $\geq$70 days.
- Registered herd, percent cows registered: <90% or $\geq$90%.
- Percentage change in cow inventory, a continuous variable, and included for its impact of net cow replacement costs.

The percentage of herds with each characteristic is presented in Table 1. Wald's test statistics for all variables (region as a group) were significant at $p < 0.1$ (2 sided), except for registered-herd. However, registered-herd was statistically significant ($p < 0.05$) in the analysis of the 'value of milking cows sold' component, which was why we chose to include it for the analysis of adjusted value of production. (Initial analysis was conducted using regression procedures of SAS (SAS Institute, 1989).)

Multicollinearity among the explanatory variables was tested by measuring the variance inflation factor (VIF) for each variable (Pedhazur, 1997 pp. 294–299). VIF measures the association of each explanatory variable in the model with all other explanatory variables in the model. The maximum association of any one explanatory variable with the others was less <50%. Thus, multicollinearity was assumed not to be a problem.

Final estimates were determined using the SUDAAN™ algorithm (Shah et al., 1997). SUDAAN™ was used to incorporate study design into the analysis (i.e. parameter estimates were weighted estimates with the weights being a function of study design – reciprocal of sampling fraction adjusted within strata for nonresponse). Of the 1004 herds that were tested for Johne's disease, 974 were usable for economic analysis.

Table 1
Head characteristics of Johne's disease and explanatory variables and association between explanatory variables and annual adjusted value of production[a] in US dairy herds

Variable	Proportion of represented herds[b] (%)	Annual adjusted value of production: regression coefficients (standard errors) (US$ per cow) Model I	Model II
Johne's disease			
Negative herds	77.8	Base	–
0% cull cows with clinical signs	51.8	–	Base
>0%, <10% cull cows with clinical signs	22.0	–	−41.93 (36.92)
≥10% cull cows with clinical signs	4.0	–	−194.85*** (55.50)
Positive herds	22.2	−97.01*** (30.90)	–
<10% cull cows with clinical signs	15.0	–	−61.23* (34.92)
≥10% cull cows with clinical signs	7.2	–	−244.94*** (47.67)
Herd size (natural log)	c	103.82*** (19.93)	98.99*** (19.93)
Region			
Midwest	60.7	Base	Base
West	8.3	−26.36 (44.94)	−31.50 (44.63)
Southeast	4.5	−216.50*** (57.49)	−231.80*** (58.41)
Northeast	26.5	−51.79 (33.83)	−60.69* (33.34)
Use Dairy Herd Improvement Association records	51.9	214.79*** (26.92)	203.45*** (26.36)
Intensive grazing Pastures supply ≥90% of summer roughage	19.5	−110.96*** (40.66)	−119.36*** (40.13)
% bovine somatotropin (bST) use (sq. root)	d	35.43*** (4.98)	36.38*** (4.73)
Bulk-tank somatic-cell count			
<200 000 cells/ml	28.9	Base	Base
200 000–399 999 cells/ml	54.0	−90.71*** (30.36)	−77.28** (30.17)
≥400 000 cells/ml	17.1	−297.60*** (43.22)	−287.63*** (42.96)
% Holstein breed	e	7.55*** (0.62)	7.51*** (0.60)
Average number of days cows were dry ≥70 days	17.6	−81.08* (41.56)	−79.91** (40.33)

Table 1 (*Continued*)

Variable	Proportion of represented herds[b]	Annual adjusted value of production: regression coefficients (standard errors) (US$ per cow)	
	(%)	Model I	Model II
$\geq$90% cows registered (yes)	12.5	60.28 (46.83)	60.63 (43.74)
% change in milk cow inventory	f	-8.95^{***} (0.70)	-8.75^{***} (0.71)
R-square		.50	.52

* Coefficients significantly different from zero at $p \leq 0.10$.
** Coefficients significantly different from zero at $p \leq 0.05$.
*** Coefficients significantly different from zero at $p \leq 0.01$.
[a] Annual adjusted value of production = value of milk + value of calf born − net cow replacement cost.
[b] Number of herds represented in analysis, 75,552; number of milk cows, 7,876,258.
[c] Continuous variable, mean herd size 104 cows (minimum 28 cows, maximum 9200 cows).
[d] Continuous variable, mean use 6.7% of cows. Of the 13.6% herds that used bST, mean use was 49.3% of cows.
[e] Continuous variable, mean 92% Holstein cows. 73.7% of herds were 100% Holstein cows.
[f] Continuous variable, mean 6.7% increase in cow numbers. 52.3% of herds had >5% increase in cow numbers, while 27.8% of herds <5% decrease in cow numbers.

To test for any differences in economic losses of Johne's disease among various herd sizes and regions, cross products between Johne's-positive herds, herd size, and region were added to Model I.

3. Model results

Our results showed that Johne's disease can be costly to dairy producers (Table 1). In Model I, Johne's-positive herds when compared to Johne's-negative herds generated US$ 97 (US$ 1916 vs. US$ 2013, $p < 0.01$) per cow less in annual adjusted value of production (AAVP). In Model II, Johne's-positive herds with <10% cull cows reported showing clinical signs consistent with Johne's disease (low-clinical Johne's-positive herds) generated US$ 61 (US$ 1996 vs. US$ 2027, $p = 0.08$) per cow less in AAVP than Johne's-negative herds with no reported cull cows with clinical signs (zero-clinical Johne's-negative herds). For Johne's-positive herds with >10% cull cows reported showing clinical signs (high-clinical Johne's-positive herds), the economic loss was US$ 245 (US$ 1782 vs. US$ 2027, $p < 0.01$) per cow.

Reduced milk production was the main factor causing Johne's-positive herds to have reduced AAVP (Tables 2 and 3). Johne's-positive herds produced 288 kg (7515 kg vs. 7803 kg, $p < 0.01$) or US$ 83 less per cow than Johne's-negative herds (Model I). Low-clinical Johne's-positive herds milked 179 kg (7665 kg vs. 7844 kg, $p = 0.15$) or US$ 51 less per cow than zero-clinical Johne's-negative herds while for high-clinical Johne's-positive herds milk production was 748 kg (7096 kg vs. 7844 kg, $p < 0.01$) or US$ 214 less per cow (Model II).

The other major cost factor associated with Johne's disease was net cow replacement costs. Net cow replacement cost was almost US$ 16 ($p = 0.08$) per cow greater for

Table 2
Marginal impact of johne's disease on dairy production parameters[a]

Dependent variables	Model I	Model II		
	Johne's-positive herds	Johne's-positive herds; Cull cows with clinical signs		
		<10%		≥10%
Milk production (kg per cow)	−288.02***	−178.65		−748.04***
Standard error	111.20	123.13		187.68
R-square	0.49		0.50	
Calves born (number per 100 cows)	2.30	1.59		3.09
Standard error	2.05	2.68		3.06
R-square	0.11		0.11	
Pregnant culls (no. per 100 cull cows)	3.25	1.21		14.48**
Standard error	3.08	3.11		5.79
R-square	0.04		0.07	
Replacement cows (no. per 100 cows)	1.60	0.97		3.27
Standard error	1.08	1.10		2.32
R-square	0.58		0.59	
Cows sold as replacements (number per 100 cows)	0.61	0.28		1.18
Standard error	0.51	0.56		1.03
R-square	0.11		0.11	
Cows slaughtered (number per 100 cows)	0.16	0.12		0.51
Standard error	0.89	0.95		1.82
R-square	0.28		0.29	
Cows died (number per 100 cows)	0.82**	0.57		1.59**
Standard error	0.39	0.44		0.72
R-square	0.10		0.10	
Poor conditioned culls (number per 100 culls)	5.66**	4.03		14.51***
standard error	2.76	2.83		5.52
R-square	0.04		0.07	

[a] For Model I, Johne's-positive herds are compared to Johne's-negative herds; for Model II, Johne's-positive herds are compared to Johne's-negative herds that had no reported cull cows showing any clinical signs of Johne's disease. Instead of having adjusted value of production as the dependent variable, the parameters listed are the dependent variables. Explanatory variables are those listed in Table 1.
** Coefficients significantly different from zero at $p \leq 0.05$.
*** Coefficients significantly different from zero at $p \leq 0.01$.

Johne's-positive herds (Model I), US$ 11 ($p = 0.22$) per cow greater for low-clinical Johne's-positive herds and US$ 32 ($p = 0.09$) per cow greater for high-clinical Johne's-positive herds than for corresponding Johne's-negative herds. Over half of the increase in net cow replacements and thus, replacement cost was due to greater mortality losses (Table 2). Johne's-positive herds mortality rate increased by 0.82 per 100 cows ($p = 0.03$) or 22% over that of Johne's-negative herds (Model I). The increase in mortality for Model IL was 0.57 per 100 cows ($p = 0.20$) or 15% for low-clinical Johne's-positive herds and 1.59 per 100 cows ($p = 0.03$) or 43% for high-clinical Johne's-positive herds. Despite a slightly greater culling rate, cull-cow revenue declined for the Johne's-positive herds in

Table 3
Marginal impact of Johne's disease on adjusted value of dairy production and its individual components[a,b]

Parameter	Model I	Model II	
	Johne's-positive herds	Johne's-positive herds; cull cows with clinical signs (US$ per cow)	
		<10%	≥10%
+ Milk value	−82.55***	−51.20	−214.39***
Standard error	31.87	35.29	53.79
+ Calves born	1.15	0.79	1.55
Standard error	1.03	1.34	1.53
− Net cow replacement cost	15.61*	10.82	32.10*
Standard error	8.84	8.80	18.95
+ Value cows sold to other producers	6.73	3.11	12.99
Standard error	5.57	6.20	11.32
+ Cull cow revenue	−4.76	−3.29	−9.09
Standard error	3.50	4.06	6.05
− Replacement cows	17.58	10.65	35.99
Standard error	11.86	12.08	25.54
= Annual adjusted value of production	−97.01***	−61.23*	−244.94***
Standard error	30.90	34.92	47.67

[a] For Model I, Johne's-positive herds are compared to Johne's-negative herds; for Model II, Johne's-positive herds are compared to Johne's-negative herds that had no reported cull cows showing any clinical signs of Johne's disease.
[b] Some columns might not total due to rounding.
* Coefficients significantly different from zero at $p \leq 0.10$.
*** Coefficients significantly different from zero at $p \leq 0.01$.

both models (Table 3). This decline cull-cow revenue was due to the statistically significant greater proportion of cull cows in poor body condition for Johne's-positive herds (Table 2) as poor body condition cull-cows received lower market prices (US$ 230 per head average) then normal body conditioned cull-cows (US$ 384 per head average).

Finally, despite culling a greater percentage of pregnant cows, Johne's-positive herds were able to slightly increase the number of calves born per cow inventory (which slightly reduced economic losses associated with the disease) (Tables 2 and 3).

Results from adding the herd size and region cross-products showed that economic losses associated with Johne's disease were greatest among large herds (≥500 cows) in the west, midwest, and northeast and small herds (<50 cows) in the midwest and northeast. However, the results were not statistically significant.

4. Discussion

Cost of Johne's disease reported in six studies varies widely (Buergelt and Duncan, 1978; Whitlock et al., 1985; Chiodini and Van Kruiningen, 1986; Benedictus et al., 1987;

Abbas et al., 1993; Meyer and Hall, 1994). To reduce the variation among the studies, costs were standardized to a common milk price and (when possible) to a common loss of reduced cull value for clinical cases. Using a milk price of US$ 286.60 per metric tonne (US$ 13 per cwt), estimated economic losses associated with Johne's disease in four of the studies ranged from US$ 401 to US$ 959 per infected cow for cows showing clinical signs of Johne's disease and US$ 123 to US$ 696 per infected cow for cows not showing any clinical signs. Across all six studies, cost of John's diseased ranged from US$ 145 to US$ 1094 per infected cow.

Even though these studies showed a wide variation in cost per infected cow with Johne's disease, they have a much narrower range of cost when based on all cows (i.e., per all cows in study population) – US$ 20 to US$ 26 per cow for all but one study. (This one study had only one herd.) NAHMS Dairy '96 Study findings can be compared to these studies by adjusting for the percentage of herds in each Johne's disease category: low-clinical Johne's-positive, 15% and high-clinical Johne's-positive, 7.2% (Table 1). Cost of Johne's disease across all herds equaled US$ 22 per cow (US$ 97.01 $\times$ 22.2%) for Model I and US$ 27 per cow (US$ 61.23 $\times$ 15% + US$ 244.94 $\times$ 7.2%) for Model II. Thus, across all herds, the Dairy '96 Study was consistent with previous Johne's disease cost estimates when common prices are used. When aggregated across all dairy cows in the US, the lost annual adjusted value of production due to Johne's disease is estimated at US$ 200 to US$ 250 million.

We expected averaged Model II results to be greater than averaged Model I results because Model II used Johne's-negative herds that had no cull cows showing clinical signs consistent with Johne's disease as the reference level but Model I used Johne's-negative herds that included cull cows showing clinical signs in the reference level. In Model II, Johne's-negative herds with <10% cull cow having clinical signs generated US$ 41.93 ($p = 0.26$) per cow less AAVP than zero-clinical Johne's-negative herds while Johne's-negative herds with $\geq$10% cull cows having clinical signs had US$ 194.85 ($p < 0.01$) per cow less AAVP. Nationally, these other diseases and conditions cost dairy producers US$ 17 (US$ 41.93 $\times$ 22% + US$ 194.85 $\times$ 4%) per cow. Obviously, other diseases causing similar clinical signs to Johne's disease (intestinal parasitism, malnutrition, salmonellosis, hardware disease, and winter dysentery) can be costly too.

Both models also demonstrated the economic importance of controlling bulk tank somatic cell counts (BTSCC) and using bovine somatotropin (BST). Herds with BTSCC in excess of 400 000 cells/ml had almost US$ 300 per cow less AAVP than herds with BTSCC less than 200 000 cells/ml (Table 1). Milk production per cow and thus AAVP rose as percentage BST use increased. Herds that used BST on two-thirds of their cows had an estimated increase in AAVP of almost US$ 300 over herds that did not use any BST (Table 1). A more comprehensive analysis of the impacts of BTSCC and BST will be addressed in subsequent papers.

One way to put into perspective the declines of US$ 61 to US$ 245 per cow in AAVP for Johne's-positive herds is to compare lost AAVP to the earnings dairy cows generate. USDA's Economic Research Service (1996) has estimated that the middle 50% of dairy producers (based on cost of milk production) earned US$ 242 per cow over cash expenses in 1993. Thus, average-cost producers with Johne's disease could have had substantially greater cash returns, if they had been free of the disease.

Model II demonstrates the importance of clinical disease prevalence and controlling the disease once it enters a herd. The decline in AAVP for high-clinical Johne's-positive herds was US$ 184 ($p < 0.01$) per cow more than that for low-clinical Johne's-positive herds (Mode II). Producers with low prevalence of Johne's disease in their herd may be tempted to accept it and focus on other management issues. Their strategy may be to wait to deal with it when its prevalence becomes high. Such a course of action is not advisable. The diagnosis and control of Johne's disease is difficult because of its chronic nature and lack of definitive tests for detection of early infection (Stehman, 1990). Also as these results suggest, such a strategy can become costly.

Risk of *M. paratuberculosis* infection increases for herds that import cows from other herds, because producers of Johne's-positive herds were at least as likely to sell replacements cows to other producers as producers of Johne's-negative herds (Table 2). This is important because *M. paratuberculosis* is usually introduced to dairy herds through the purchase of infected cattle (Sweeney, 1996). Even though the statistical significance of this association was low, the occurrence of sales from high-risk herds should serve as a warning to producers to be careful about purchasing cattle and to select cows only from herds free of Johne's disease.

This study was cross-sectional in design and losses were estimated at the herd level. It was not possible to distinguish between clinical and subclinical losses. Johne's disease can have a latent period of 2 to 5 years (Stehman, 1990) – which can result in many cows being infected for every cow showing clinical signs (Whitlock and Buergelt, 1996). Buergelt and Duncan (1978) found that milk-production loss for subclinical cows with Johne's disease was almost half of the quantity lost by Johne's cows with clinical signs. Thus, it is reasonable to assume that some of the lost milk production associated with Johne's disease reported in Table 3 could be attributed to subclinical cows.

One limitation to this study was that costs (except for cow replacements) were not included. Feed – the greatest expense on a dairy operation (USDA:ERS, 1996) – is related to milk production because higher-producing cows require more nutrients (National Research Council, 1989). With Johne's-positive herds producing less milk, one might expect their feed input per cow to be lower which would reduce the economic impact of the disease. Johne's disease, however, causes chronic diarrhoea and weight loss that is nonresponsive to treatment despite a normal appetite (the pathogenic mechanism includes intestinal malabsorption). Thus, if cow appetite remains normal, Johne's-positive herds would be expected to consume similar quantity of feed per unit of milk as Johne's-negative herds. Future research could test this hypothesis.

Other costs (such as labour and capital charges) are generally a function of the number of cows within the herd and should not affect study results substantially. In this study, producers were asked to report their cost of producing milk in US$ 11 per metric tonne (US$ 0.50 per cwt) intervals. Unfortunately, several producers did not provide this information and there was much variation in the cost estimates. Therefore, while the inclusion of costs would be preferable, they were not included due to poor data quality and quantity.

In summary, economic losses associated with *M. paratuberculosis* in US dairies can be substantial and occurs across all herd sizes and regions. Lost milk production and higher net cow-replacement costs contributed to decreased value of production per cow inventory in Johne's disease inflected herds. Economic losses became highly significant (US$ 245 per cow annually) when percentage of culled cows showing signs consistent with Johne's disease exceeded 10%. Such a high annual cost offers incentive to producers with positive herds to initiate a Johne's-disease-control programme and to producers of negative herds a strong incentive to implement a biosecurity program to keep Johne's disease from entering their herds. Nationally, Johne's disease is estimated to cost the dairy industry US$ 22 to US$ 27 per cow annually in lost revenue and increase cow replacement costs.

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